DISCUSSION PAPER NO.44

Moore's Law, Increasing Complexity and Limits of Organization: Modern Significance of Japanese DRAM ERA

March, 2007

Hiroyuki Chuma and Norikazu Hashimoto

1st Theory-Oriented Research Group
National Institute of Science and Technology Policy (NISTEP)
Ministry of Education, Culture, Sports, Science and Technology (MEXT)

ムーアの法則がもたらした複雑性増大と"組織限界"
—日本の DRAM ビジネス盛衰の現代的意義を探る—

2007 年 3 月

中馬宏之　一橋大学イノベーション研究センター　教授
文部科学省科学技術政策研究所　第 1 研究グループ客員総括主任研究官
橋本哲一　文部科学省科学技術政策研究所　第 1 研究グループ客員研究官

〒100-0005　東京都千代田区丸の内 2-5-1　文部科学省ビル 5 階
Email: 1resgr@nistep.go.jp　TEL: 03-3581-2396　FAX: 03-5220-1253

Moore's Law, Increasing Complexity and Limits of Organization:
Modern Significance of Japanese DRAM ERA

March, 2007

Hiroyuki Chuma and Norikazu Hashimoto

1st Theory-Oriented Research Group
National Institute of Science and Technology Policy (NISTEP)
Ministry of Education, Culture, Sports, Science and Technology (MEXT)

2-5-1 Marunouchi, Chiyoda-ku, Tokyo 100-0005
Email: 1resgr@nistep.go.jp　TEL: 03-3581-2396　FAX: 03-5220-1253

Moore's Law, Increasing Complexity and Limits of Organization: Modern Significance of Japanese DRAM ERA

Hiroyuki Chuma and Norikazu Hashimoto

Contents

Moore's Law, Increasing Complexity and Limits of Organization:[1] Modern Significance of Japanese DRAM ERA[2]

Hiroyuki Chuma[3] and Norikazu Hashimoto[4]

1. Introduction

There has been growing interest in innovations[5] in which creative inventions and discoveries made in a wide variety of fields of science and technology bring about changes to social life through markets. A tendency like this is especially pronounced in innovations in science-based industries[6] (referred to as "science innovation"). One of the reasons why there has been growing interest is that, as a result of the rapid development of information technology with semiconductor technology at the core, complexity has been increasing not only for technology but for markets as well. And such a tendency is further accelerating due to people's diversified and upgraded preferences brought on by affluence, and the globalization of the whole economy.

Under the circumstances where the complexity of the technology and market is drastically increasing, there is an unavoidable tendency for specialization to occur between people engaging mainly in creating science knowledge (hereinafter referred to as knowledge) and those engaging in utilizing such knowledge. This is because the range and depth of the knowledge needed for creation and utilization frequently goes beyond the limits of a particular individual's information-processing capability. Moreover, along with the increasing complexity and specialties of the knowledge to be created, the level of difficulty in utilizing such knowledge in an integrated way will rapidly rise at no inferior pace, as is exemplified also by the increase of the service economy.

---

[1] Experienced law that the degree of integration of semiconductor doubles in two years or three years Moore's Law. Certain G. Moore, one of Intel initiators, advocated it. Refer to http://www.intel.com/technology/mooreslaw/index.htm for details. DRAM is abbreviation of Dynamic Random Access Memory.

[2] In writing this paper, we got large support from a lot of semiconductor research scientists and engineers such as Professor Hideo Sunami (Research Center for Nanodevices and Systems, Hiroshima University), Dr. Kiyoo Itoh (Central Research Laboratory, Hitachi Ltd. Fellow), and Dr. Hideaki Khozu (former chief engineer of NEC). We want to express our gratitude to them deeply on this occasion. Of course, all the blame of this paper belongs to the author. At the US patent analysis, we are very indebted to Mr. Toshiaki Fukano (National Institute of Science and Technology Policy) who had prominent professional technique in the software development for semiconductor-fabrication equipment. It goes a lot in the US patent analysis related to the semiconductor process technology in the text. In that case, retrieval by keyword over the patent full text was done based on advice by the specialist in the semiconductor field. The detail of the method of retrieval by keyword was omitted for the convenience of space.

[3] Professor and Affiliated Director, Institute of Innovation Research, Hitotsubashi University and National Institute of Science and Technology Policy

[4] Visiting researcher, National Institute of Science and Technology Policy. Former research director of Central Research Laboratory, Hitachi Ltd.

[5] In this paper, the innovation is defined as "creative discovery and invention that can bring the social life revolutionary changes through the market". Therefore, the innovation contains not only what achieved ex post but also the one with big potential possibility of achieving them.

[6] The science-based industry is an industry such as the semiconductor, the pharmaceuticals, and biotechnology. In this industry, a scientific discoveries and inventions tend to be related directly to products.

As a result, it becomes quite common that the knowledge–utilizing speed itself becomes a critical contributing factor for innovation. This is because under such circumstances, Papert's Principle, a general principle of the increasing complexity in the field of artificial intelligence, will gravely stand in the way, even in terms of the industrial level (Minsky (1986), (2006))

Papert's Principle: "Some of the most crucial steps in mental growth are based not simply on acquiring new skills, but on acquiring new administrative ways to use what one already knows."

In reality, in order to effectively and promptly realize innovation in science-based industries, it is necessary to have a mechanism to extensively and promptly mobilize people with special knowledge of a different nature inside and outside the corporation. However, in order to realize an extensive and prompt mobilization, it is indispensable to have a new organizational management style to promote the autonomous mobilization of specialists from a wide variety of fields. In addition to that, a mechanism is required to accelerate the speed of accumulatively creating new knowledge by enhancing the interchangeability of the knowledge held by mobilized specialists and raising the efficiency of reuse of such knowledge.

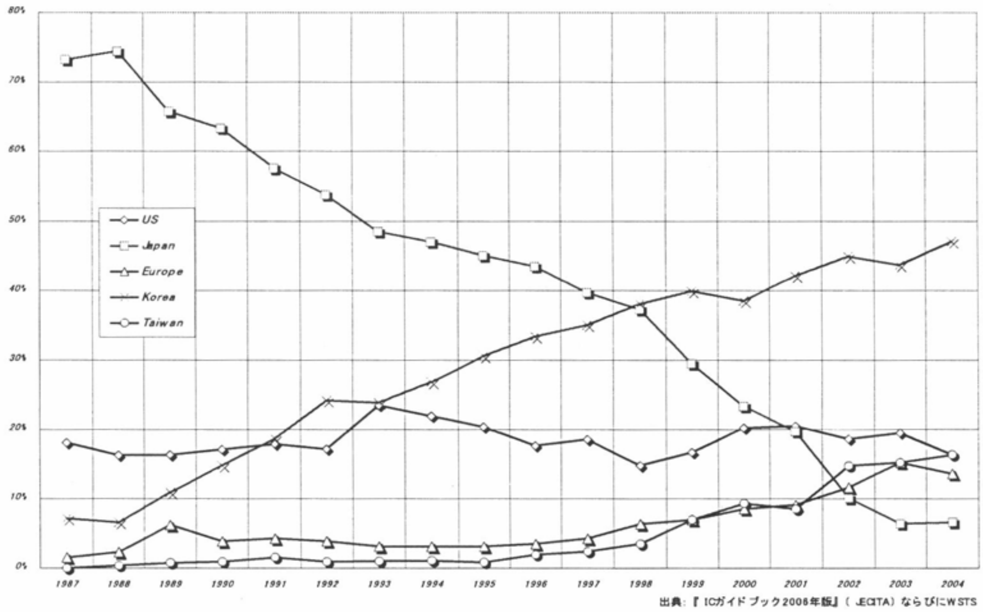
Unfortunately, in Japanese science-based industries, as the complexity of the technology and market has started to exceed the threshold value, it has become difficult to promptly realize the mobilization of knowledge inside and outside the organization at a sufficiently extensive level (e.g., Chuma (2006)). As a result, the limits of the organizational management style (referred to as "limits of organization") with regard to the drastically increasing complexity of the technology and market are appearing everywhere. And even in the fields where a great number of discoveries and inventions have been created, there has started to occur a tendency for the competitiveness of the related science-based industries to weaken, due mainly to the delay in the speed of effectively utilizing such knowledge.

The purpose of this paper is to identify the contributing factors of the weakening compositeness of Japanese science-based industries and search for measures to overcome these factors, based on the awareness of the issues mentioned above. For this purpose, the case of the semiconductor industry, which is one of the typical science-based industries, especially the process of the rise and fall of the DRAM business experienced by this industry, is used for analysis. While attempting to do so, we make a unique trial through the following two analyses: (1) the analysis of the analytical report in detail (by using the electronic microscope) concerning the mass-produced DRAMs manufactured by the Japanese, U.S. and South Korean manufacturers during several generations, and (2) the analysis of the micro- and macro-attributes of the research and development activities of each manufacturer based on the DRAM-related patents of Japan and the U.S. over several decades and the academic papers of the major academic societies represented by

ISSCC (International Solid-State Circuit Conference) and IEDM (International Electronic Device Meeting).

In this paper, based on these analyses, we explain the condition of technological competition among the major manufacturers regarding DRAMs not only in the stage of research and development but also in the stage of mass production. Next, based on these results, we pin down the more detailed fact regarding the condition of increasing complexity of the technology with the other conditions made constant. Also, considering the technological attributes derived through the analyses, we make an in-depth examination of the characteristics of DRAM market. Finally, based on the results of these analyses we make an inquiry into issues like "Why did nearly all of the Japanese semiconductor manufacturers retreat from the DRAM business?", "What is similar between this and the contributing factors of the weakening competitiveness being faced nowadays by the Japanese semiconductor manufacturers?" and "What is considered as necessary for overcoming these contributing factors of the weakening competitiveness?"

Figure 1: Share of DRAM Shipment($) by Nationalities



出典：『ICガイドブック2006年版』（JEITA）ならびにWSTS

2. Stylized facts of Japanese DRAM Era: Rise and Fall

From the process of the rise and fall of the DRAM business observed during the past 30 years, we can find the following four types of stylized facts.

(SF1) The Japanese manufacturers secured a share of more than 70% of the DRAM shipment worldwide till the end of the 1980s, but after that the share drastically declined and is less than 10% nowadays.

(SF2) The Japanese manufacturers have had a lead in the design and the processing (manufacturing) technology of DRAM worldwide for every type of DRAM, from 64Kb to 256Mb. Even today, these technological advantages have not been lost.

(SF3) For 64Mb or larger DRAMs (more evidently 128Mb), Samsung in South Korea became the first-mover, while, for the (memory) chip–size and cell–size[7] of 16Mb or larger DRAMs, Micron in the U.S. became the winner of the shrinking technology.

(SF4) From the second half of the 1990s onward, (with Elpida as an exception) the Japanese manufacturers lost their advantages in terms of the production system as measured by the indicators such as the cycle time and the delivery time.

Below, first let's confirm these points by showing relevant evidence.

Table 1: DRAM-Related Papers in ISSC and IEDM by Chipmakers

1) ISSCC (DRAM-related) * means one paper

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Hitachi	*		*		**	***		**	**	**		**		**		**			*	*	*	*		
Toshiba	**		**	*		***	***	*	*	*		**		*		**			**	**	**			
NEC	*	*		**	*	*	*			*			*	*	*	*	**	**	*	***				
Mitsubishi Elecatric																								
Fujitsu				**	*	*		*				*						*	**					
IBM		*	**	*	**	*		*	**		*	*							***	*	*	**	*	
Intel		*	***	**	*		*							*										
Micron																								
Mostek					*	*	*																	
Motorola				*			*											*	*					
Texas Instruments	*						**	*	*									*						
Infineon + Siemens					*			*	*										*	**		*		
Samsung																	*	**	*	**		*		
Hynix + Hyundai + LG																			**	*	*		*	

2) IEDM (DRAM-related)

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Hitachi	*	*	*		**	***	**	*	*			*	**		*	**		*	***	***	*	*		**
Toshiba		**		*	**	**		*	*	****	*	***		****	**	**	**	***	****	***	***	**	**	**
NEC	*				*	*	*	*		*	*	*****	****	*	***	****	****	***	*****	**	**	*	*	
Mitsubishi Elecatric	*		*		*		*	*	*		*	*	*	***		**	****	*	***	*				
Fujitsu								*	*		*	*	*			*	*	**	*	**	**			**
IBM				*		*		*	***	*	*	**	****	*		*	*	**	*	***	*	****		**
Intel			*																					*
Micron											*	*	*	*										
Mostek					*																			
Motorola												*	**		**	*								
Texas Instruments					*	**	**	*	*	**					*		**	*		*				*
Infineon + Siemens														*			*	*		***	*	*****	***	**
Samsung														*	*****	**	****	*	****	**	***	***	*****	****
Hynix + Hyundai + LG																***		**	*		*	**	**	

Sources: IED Sources: IEDM 50 Years、ISSCC 50 Years

2.1 Confirmation of the stylized fact (SF1)

SF1 can be immediately confirmed through Figure 1 which shows the DRAM shipment by region. In reality, we can see that the share of the shipment accounted for by Japanese players

[7] The segment cut out from the wafer in which the processing ends is a chip. As for the chip, the packaging is done with plastic etc. It is a memory module that we make usually that is called SIMM and DIMM that puts those eight chips. The memory cell is modularization of one transistor and one capacitor. A lot of these memory cells are contained in one DRAM chip. The transistor is an element (component) to which (0-1) information is created by the added voltage's exceeding a specific threshold and falling below.

drastically declined from the end of the 1980s onward.[8] During this period, Fujitsu retreated from the business in December 1998, Toshiba in December 2001, and Mitsubishi Electric in October 2002. In addition, NEC and Hitachi span off the DRAM business from their main businesses and jointly established Elpida, a DRAM specialty company, in December 1999. As a result, Elpida has become the only DRAM manufacturer remaining in Japan.

2.2 Confirmation of the stylized fact (SF2)

Regarding 64Kb or larger DRAMs, many of the processing and design technologies which form the essential part have come from Japan (Hitachi in particular) and the U.S. (IBM in particular). The specific examples will be discussed in detail in the second half of this paper, but such a condition can be confirmed from Table 1 as well. This table shows the condition of academic paper presentation by the major DRAM manufacturers in Japan, the U.S., South Korea and Germany at ISSCC (front-end process) which is an international conference mainly for the presentation of the semiconductor design technology and at IEDM (manufacturing process) which is an international meeting for the presentation of the processing (manufacturing) technology.

The DRAM-related academic papers by each manufacturer at ISSCC consist of approximately two pages in many cases. And because of this, in the 1980s, it took on a strong character as a conference for presenting products. In reality, at the time of presentation, each manufacturer already completed the patent application with an awareness of going into mass production two years later. For such a reason, in the case of ISSCC, many of the technologies presented were related to development (utilization of science knowledge). On the other hand, in the case of IEDM, the academic papers included many ones related to research (creation of science and knowledge) if compared to the case of ISSCC.

If we look at the condition of research and development of each manufacturer as was indicated by ISSCC and IEDM (refer to Table 1), it can be inferred that from the second half of the 1980s to the second half of the 1990s, the Japanese manufacturers were actively involved in both the processing and design technologies. In addition, it has become evident that in any of the periods, IBM continued to maintain its role as a leader not only in development but in research as well. On the other hand, in contrast to the Japanese manufacturers and IBM, Micron had not presented its research results at either of the societies for a long time. The same also applies to the South Korean manufacturers (Samsung and Hynix) till the second half of the 1990s. In other words, at least till the second half of the 1990s, both Micron and Samsung were companies of the knowledge utilization type (or the type of seeking after profits generated from mass production). In the case of

[8] Retrieval by keyword was done based on the advice of the specialist.

Micron, this tendency has consistently remained even till the present.[9] However, starting in the second half of the 1990s, Samsung rapidly increased its presentation at IEDM especially regarding the processing technology.

2.3 Confirmation of the stylized fact (SF3)

Regardless of the advantages in the research and development capability as was confirmed in the previous section, with respect to 64 Mb or larger DRAMs for which technology complexity is said to drastically increase, the Japanese manufacturers start to lag behind Samsung in terms of the speed of mass production and behind Micron in terms of the chip-size shrinking technology. The former can be confirmed in Table 2 in a more detailed way. The first row of Table 2 shows the capacity of a memory package, and the first line shows the items such as the year of presentation, the manufacturer of presentation at international meetings like ISSCC, the starting year of mass production, and the starting manufacturer. According to this table, for 64 Mb or larger DRAMs, the time from development till mass production, the time till mass production of 1 million pieces, and the time from development till the production of the said DRAM reached the peak were all prolonged. In other words, technology complexity has drastically increased.

Table 2: Transition in DRAM Development and Commercial Production by Memory Density

DRAM-Size (Bit)	Presented Year in ISSCC, JSSC, VLSIC (A0)	Presented Makers	Year in First Commercial Production (A1)	First Commertial Production Maker	(A1-A0)	Year when a million number of shipments was attained (A1)	(A2-A0)	Peak Year of Number of Shipments (A3)	(A3-A0)
1K	Nothing		1971	INTEL	-	1973	-	1974	-
4K	1973	INTEL	1975	TI	2	1975	2	1979	6
16K	1976	INTEL, Hitachi	1977	Mostek	1	1977	1	1982	6
64K	1978	Mostek, NEC, NTT, Siemens	1980	Hitachi	2	1980	2	1987	9
256K	1980	NEC, NTT	1983	Fujitsu	3	1983	3	1988	8
1M	1984	Hitachi, NEC, NTT	1986	Toshiba	2	1986	2	1991	7
4M	1986	NEC, TI, Toshiba	1989	Hitachi	3	1989	3	1995	9
16M	1988	Hitachi, Matsushita, Toshiba	1991	Hitachi	3	1993	5	1997	9
64M	1991	Hitachi	1994	NEC, Samsung	3	1996	5	2000	9
128M	Nothing	Nothing	1998	Samsung	-	1998	-	2001	-
256M	1993	Hitachi, Matsushita, Mitsubishi, Toshiba	1997	Samsung	4	1999	6	2005	12
512M	Nothing	(IBM:2001)	2003	Samsung	-	2003	-	2008E	-
1G	1995	Hitachi,	2004	Samsung	9	2004	9	2009E	14

Sources: ISSCC, JSCC, SVLSIC, SEMICO(2003), ICE(1997), Nikkei-Shinbun
JSCC= Jounarl of Solid State Circuits, SVLSIC= Symposium on VLSI Circuit

[9] The number of papers that each company made public to the professional journal was retrieved by Science Direct. Hitachi was 1993, Central Research Laboratory, Hitachi Ltd. was 837 consequently, NEC was 826, Samsung Electronics Co., Ltd. was 314, Samsung Advanced Institute of Technology was 435, and Micron was 25. This result frankly tells that Micron is an enterprise of a typical knowledge utilization type.

Under these circumstances, the Japanese manufacturers' research and development capability accumulated from the 1980s onward failed to lead to mass production in an early stage. In reality, for 16 Mb DRAMs or smaller ones, Japanese players' speedy development and mass production had the upper hand. Nevertheless, for 64 Mb or larger DRAMs, Samsung started to outpace the Japanese manufacturers in terms of the time to start mass production. As a result, Samsung which should have so far been a manufacturer of the knowledge utilization type started to gain profits not only from mass production but also profits as a leader.

Regarding the condition of chip- and cell-size shrinking at the level of mass-produced DRAMs, the properties of Micron's 16 Mb DRAMs were notably seen (refer to Table3). In this table, both the chip- and the cell-sizes were converted into relative numerical values by using the size of NEC16M_1 (the actual model wasμPD4216100) in 1991 as a benchmark. The DRAMs manufactured by each company are the mass-produced products actually manufactured and put on the market. NEC shrank the size to 71% from 1991 to 1996. However, two of Micron's chips were shrunk to 41% and 28% in 1996 and even to 20% in 1997. This is a shrinking technology worthy of surprise. This shows why other companies in the industry failed to compete with Micron during 1996 and 1997. Incidentally, the overwhelming presence of Micron in the DRAM market in 1997 was called "Micron shock" in Japan.

Table 3: Trend in Chip Size and Cell Size Shrinking

Product	Expected Year	Chip Size (HEC_16M_1=100)	Cell Size (NEC_16M_1=100)
NEC16M_1	1991	100.00	100.00
Fujitsu16M_1	1992	94.71	113.10
Samsung16M_1	1993	67.55	86.67
Mitsubishi16M_1	1994	69.71	71.43
Hitachi16M_1	1994	65.96	75.30
Hitachi16M_2	1994	67.90	76.19
NEC16M_1	1994	68.64	71.43
Samsung16M_2	1994	63.72	65.48
Hyundai16M_1	1994	86.18	95.24
Fujitsu16M_2	1995	68.11	61.90
NEC16M_2	1996	71.24	74.04
OKI16M_1	1996	73.82	77.38
MoselVitelic16M_1	1996	62.67	65.48
Micron16M_1	1996	40.60	35.48
Micron16M_2	1996	27.51	35.48
ShinNipponSteel_1	1997	69.64	130.95
Micron16M_3	1997	20.06	不明

出典: Chipworks社、Semiconductor Insights社、http://smithsonianchips.si.edu/ice/s4.htm

2.4 Confirmation of the stylized fact (SF4)

How the Japanese semiconductor manufacturers lost their advantages in terms of the production system was obviously shown by the results of the survey conducted by UC Berkley

(Leachman and Hoges (1996)) in the 1990s. According to the results of this survey, as is shown in Table 5, the U.S. semiconductor manufacturers considerably outpaced the major Japanese semiconductor manufacturers even at that time in terms of not only the cycle time per layer (time needed to process one piece of mask) but also the delivery on time. Nevertheless, the Japanese semiconductor manufacturers still had the upper hand in terms of the yield (rate of yield per wafer) and the utilization efficiency of the microlithography.

The tendency for the gap between Japan and the U.S. to rapidly narrow in terms of competitiveness in the semiconductor production system already started in the late 1980s. Regarding this, Macher *et al.* (1998) showed that at the beginning of the 1990s, the gap between Japan and the U.S. had considerably narrowed in terms of not only the cycle time but also other indicators such as the probe yield at the stage of the probe test (conducted after the completion of a chip), labor productivity per direct worker, and the defect density.

Regarding the condition in the second half of the 1990s, there is no literature available for a clear international comparison like Table 5. However, Leachman *et al.* (2002) exhibited a condition of time shortening in all of Samsung's semiconductor factories from 1996 onward. Leachman played a leading role as consultant at that time. According his academic paper, as a result of the production system reform that started in 1996, the total cycle time (TAT: Turn Around Time) of 64 Mb DRAMs was shortened from 90 days in early 1996 to a little more than 30 days in late 1998. It is difficult to make a pure comparison, but 30 days is a numerical value considerably lower than the then level (around 60 days) of a certain Japanese manufacturer of which a fact-finding inquiry was conducted.

Table 4: Japan-US Comparison in Fab Performance in the early 1990s

TABLE II

SUMMARY OF TECHNICAL METRIC SCORES, COMPETITIVE SEMICONDUCTOR MANUFACTURING SURVEY (FIRST 18 MONTHS)

Metric	Best score	Average score	Worst score	Japan vs. US
Cycle time per layer (days)	1.2	2.6	3.3	–
Line yield per ten layers (%)	98.9	92.8	88.2	++
Murphy defect density - (defects/cm^2)				Overall: ++
0.7 - 0.9 micron CMOS memory	0.28	0.74	1.52	
0.7 - 0.9 micron CMOS logic	0.28	0.79	1.94	
1.0 - 1.25 micron CMOS logic	0.23	0.47	0.96	
1.3 - 1.5 micron CMOS logic	0.21	0.61	1.15	
5X stepper throughput (5X layers completed per machine-day)	724	382	140	+
Direct labor productivity (wafer layers completed/operator-day)	63.0	29.6	8.0	+
Total labor productivity (wafer layers completed/total staff-day)	37.7	17.6	3.3	++
On-time Delivery (% of line items with 95% of die output on time)	100%	89%	76%	–

Average and worst scores are calculated after discarding the worst data sample for each metric. Legend:

++ Japanese fabs are almost uniformly superior
\+ Japanese fabs are generally superior
0 Superior/inferior fabs are not distinguished by region
– US fabs are generally superior
— US fabs are almost uniformly superior

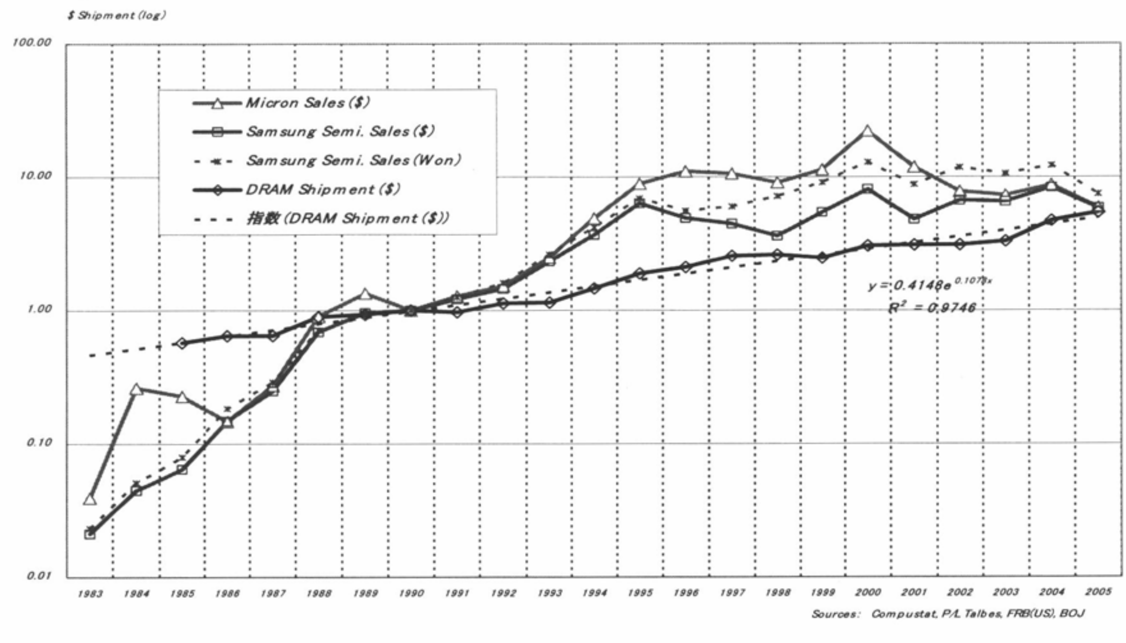
Sources: Leachman and Hoges (1996)

3. The impact of the Japan-US agreement on semiconductor trade

Up till now, many people have repeatedly tried to explain some of the four stylized facts (SF1 to SF4) in a fragmentary fashion. And they have made various explanations such as the insufficient scale of investment in semiconductor-equipment and the delayed timing of investment due to mistaken business judgment, the delay in the cognition of the structural changes of the DRAM market triggered by the advent of PCs, the various restrictions imposed on the Japanese manufacturers under the Japan-US agreement on semiconductor trade, and the decline in price competitiveness due to the drastic yen appreciation.[10] On account of space considerations, we cannot examine these viewpoints in detail in this paper but we want to touch upon the impact of the Japan-US agreement on semiconductor trade which is considered to be particularly important.

Pressure on the Japanese manufacturers from the U.S. government under the Japan-US agreement on semiconductor trade was so strong that it went beyond our imagination today (Ohyane (2002)). The results are shown in Figure 2, though indirectly. The vertical axis of this table follows the change from 1983 till 2005 by using as a benchmark the semiconductor-related sales amounts of Micron[11] and Samsung in 1990. Regarding Samsung, the change expressed in won (dotted line), too, is shown. In addition, for the purpose of making a comparison, the change in the DRAM shipment (in U.S. dollars) worldwide is also shown along with the straight line (dotted line) approximated by the exponential function. As is shown in the figure, the shipment worldwide can be estimated in an almost perfect manner by a 10% downward-sloping straight line.

Figure 2: Transition in Semiconductor Shipment($) (1990=1): Micron, Samsung, DRAM Total



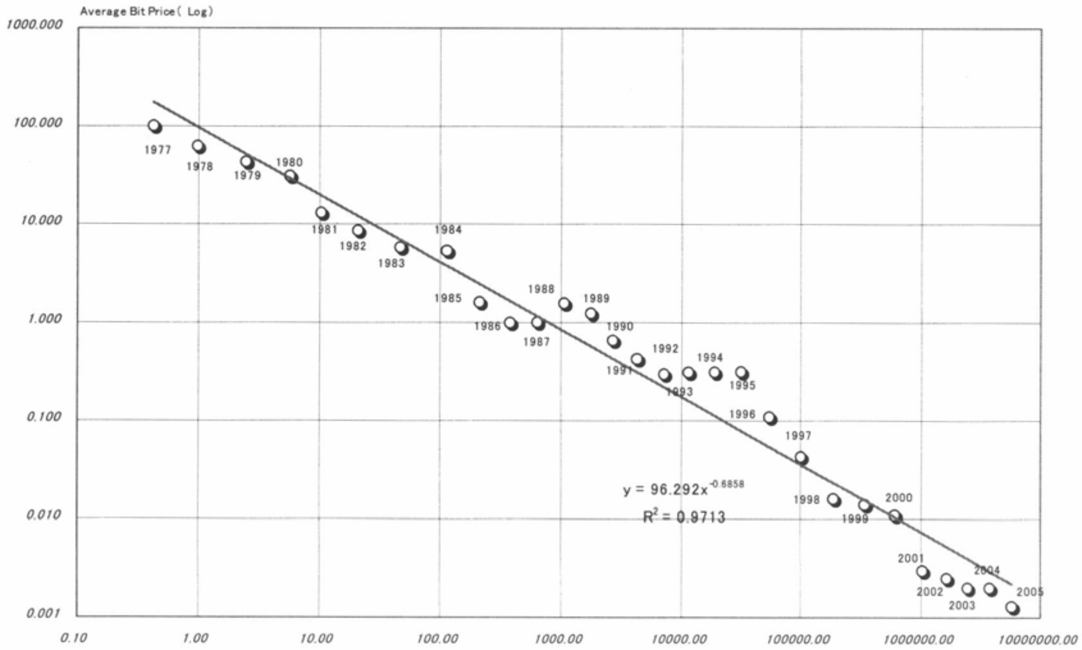
---

[10] Refer to Yoshioka (2004) for details or more.

[11] Established in 1978, production started in 1982

As can be easily understood from this figure, from 1986, the year when the Japan-U.S. agreement on semiconductor trade went into effect, till 1995, both Micron and Samsung achieved a growth rate of around 40%, a rate by far higher than the growth rate of the worldwide DRAM shipment (10%). In particular, regarding Micron, as a result of a serious semiconductor slump starting in 1985, its sales amount drastically dropped from 1984 till 1986. However, from 1987 onward, it immediately followed the path of rapid growth.[12]

Figure 3: Transition in DRAM Bit Price vs the Amount of Cumulative Bits



Source: ICE(1997) and McClean Report (2006)

The rapid growth achieved by Micron and Samsung was underpinned by the drastic and significant increase in DRAM prices brought on by the limited supply under the Japan-U.S. agreement on semiconductor trade. In reality, according to Johnson *et al.* (1988), the cost of a 4 Mb DRAM was approximately four dollars around 1992 but it was sold at around twelve dollars in the (spot) market. This can be clearly confirmed through the movement on the trend line of the average DRAM price per bit shown in Figure 3. The vertical axis of this figure stands for the average DRAM price per bit (logarithm) and the horizontal axis for the accumulated bit capacity of DRAMs with a different memory capacity.[13] Between the annual changes in the price per bit and the accumulated bit capacity, a relationship can be established in an almost perfect way (with a

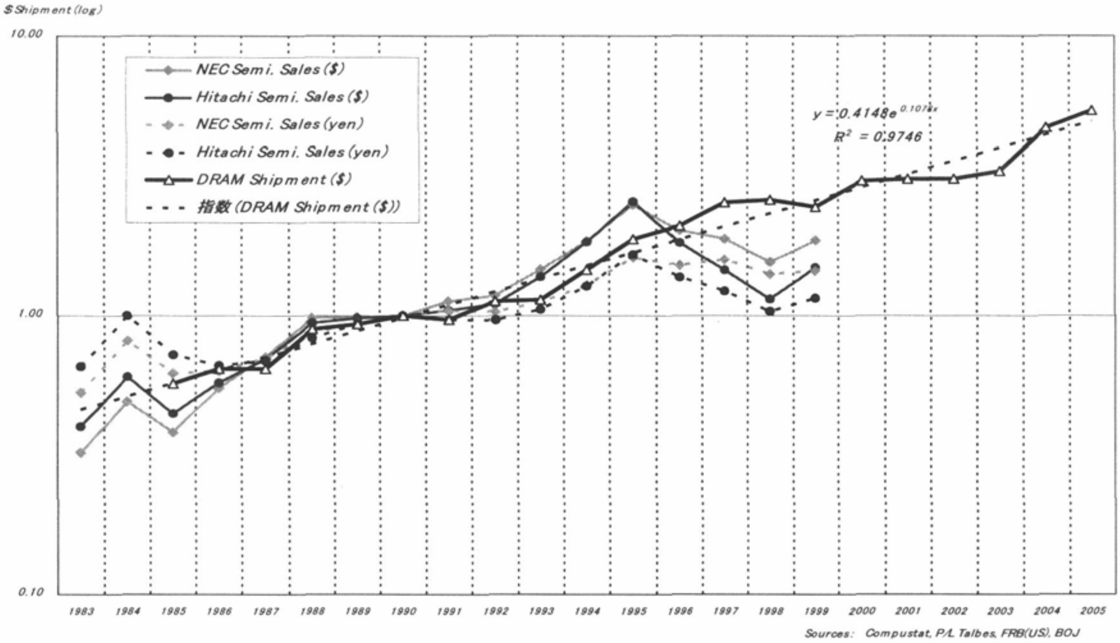
[12] The growth rate of sales volume measured by the dollar immediately after 95 years declines considerably for Samsung. The growth rate of sales volume measured by the won rises a little bit. This reflects rapid won depreciation by "IMF Foreign Exchange Crisis" in 1997 and the won depreciation tendency to have continued for several years afterwards.

[13] The bit capacity of each year is calculated in shape to multiply the bit capacity and the quantity of production of various DRAM produced in the same year. The accumulated bit capacity of each year is an amount in which they are added up to a year concerned in 1977 and matched.

determination coefficient of 97%) by using the straight line shown in Figure 3. According to this figure, the DRAM price drastically rose after the Japan-U.S. agreement on semiconductor trade went into effect and drastically dropped (to approximately one-fifth) from 1995 onward, but till 1977 it lay almost above the trend line.

From the above facts it is known that behind the emergence of the powerful manufacturers as substitute suppliers of DRAM like Micron and Samsung, the drastic increase in DRAM prices under the Japan-U.S. agreement on semiconductor trade had a significant impact. However, drastically rising DRAM prices should have brought about great profits for the Japanese manufacturers even if supply was restricted. Figure 4 gives us a reply to this issue. The vertical and horizontal axes are the same as in Figure 2, but the reduction scale of the vertical axis is twice as large as that of Figure 2, reflecting the low growth rate of the Japanese manufacturers. In addition, the DRAM divisions of Hitachi and NEC were merged around late 1999 to become today's Elpida. Because of this, no data is available for each of the two companies after 1999.

Figure 4: Transition in Semiconductor Shipment (1990=1): Hitachi, NEC

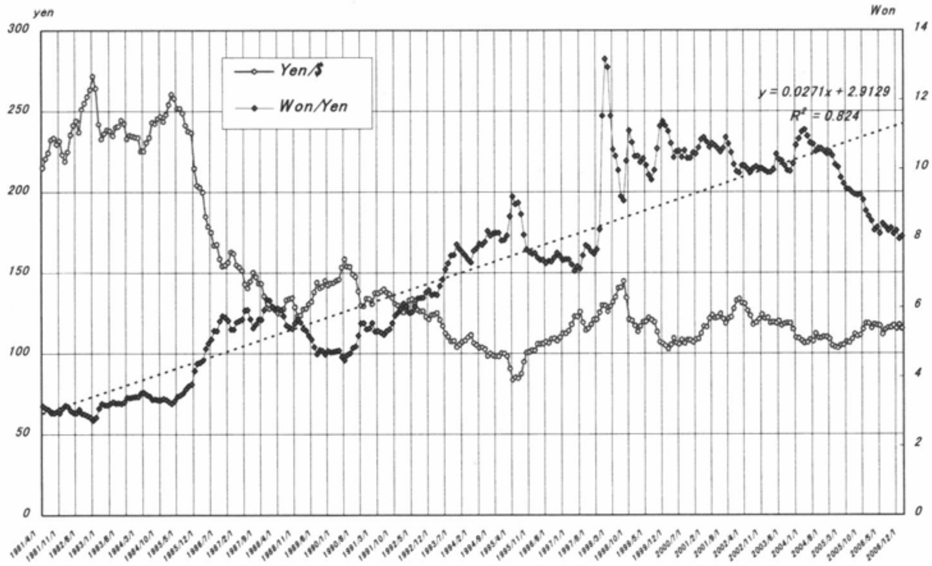


Sources: Compustat, P/L Talbes, FRB(US), BOJ

According to Figure 4, the Japanese manufacturers grew almost at the same rate of 10% as the growth rate of worldwide DRAM shipment till 1995. In this sense, effects from the bubble economy burst in early 1990 did not occur at least till the first half of the 1990s. In reality, as of this point in time, the share accounted for by the Japanese manufacturers in the worldwide DRAM shipment still outpaced the South Korean manufacturers by more than 10%, as is shown in Figure 1. Nevertheless, along with the drastic decline in DRAM prices starting in 1996, both Hitachi and NEC started to post significant negative growth. The same condition can be confirmed for Toshiba, Fujitsu and Mitsubishi Electric, though they are not shown in the figure. In addition, as a reflection of the trend of the yen depreciation in the 1980s and the trend of yen appreciation in the first half of the 1990s, the growth rate of the sales amount indicated by dollars shows a deviation larger than if indicated by the yen.

Therefore, the reason for the deceleration of the Japanese manufacturers from 1995 onward cannot be entirely attributed to the Japan-U.S. agreement on semiconductor trade and the exchange rate. In reality, during the period of the second Japan-U.S. agreement on semiconductor trade from 1991 till 1995, the situation was not so frantic as in the first period (Ohyane (2002)). However, under the Japan-U.S. agreement on semiconductor trade, due partly also to the support from the Japanese government, all of the major semiconductor manufacturers except Toshiba made investments in the overseas factories of front-end semiconductor equipment, which may also be said as reckless if judged by today's criteria. Moreover, (in cases where there was no binding force through an agreement with the government of the country where such investments were made) those factories were inevitably closed or retreated without exception. This is considered to have, to a considerable extent, deprived the Japanese manufacturers of their surplus funds to make investments thereafter.

Figure 5: Transition in Yen/$ and Won/Yen: 1981 to 2006



It is necessary to note the trend in yen/dollar exchange rates and won/yen exchange rates as one of the factors to support the great progress of Samsung in the latter half of the 90's. First of all, the depreciation in yen in the first half of the 1980s was almost solved in about 1990, and showed cyclical movement to make 120 yen bottom about yen/dollar exchange rates afterwards. In this sense, yen/dollar rates in the latter half of the 1980s were a fair wind for Micron. In contrast, after

1990, the yen/dollar exchange rates hardly influenced Micron. On the other hand, Samsung's circumstances were quite different. Actually, won/yen exchange rate had continued to depreciate about 0.3 won in one year for about 25 years. Additionally, did the occurrence of remarkable won depreciation in 1997 because of the currency crisis of South Korea. The subsequent won depreciation tendency continued up to the beginning of 2002. Together with the price cutting tendency after the collapse of DRAM at 1995 year-end, such won/year depreciation became very hard to deal with for Japanese semiconductor chipmakers.

4. A new view of internal cause in the rise and fall

In order to explain in a consistent manner the logic generated from (SF1)-(SF4), it is necessary to establish an organic relationship between (SF3) which shows the decline in the speed of mass production and (SF4) which shows the decline in the efficiency of the production system. And in order to do so, it will be necessary to make a somewhat more detailed examination of the attributes of the DRAM technology and the structural changes in the market for which the year of 1995 marked a boundary. This is for the purpose of understanding the drastically widening scope for utilizing knowledge caused by the drastically increasing complexity of the technology and market.

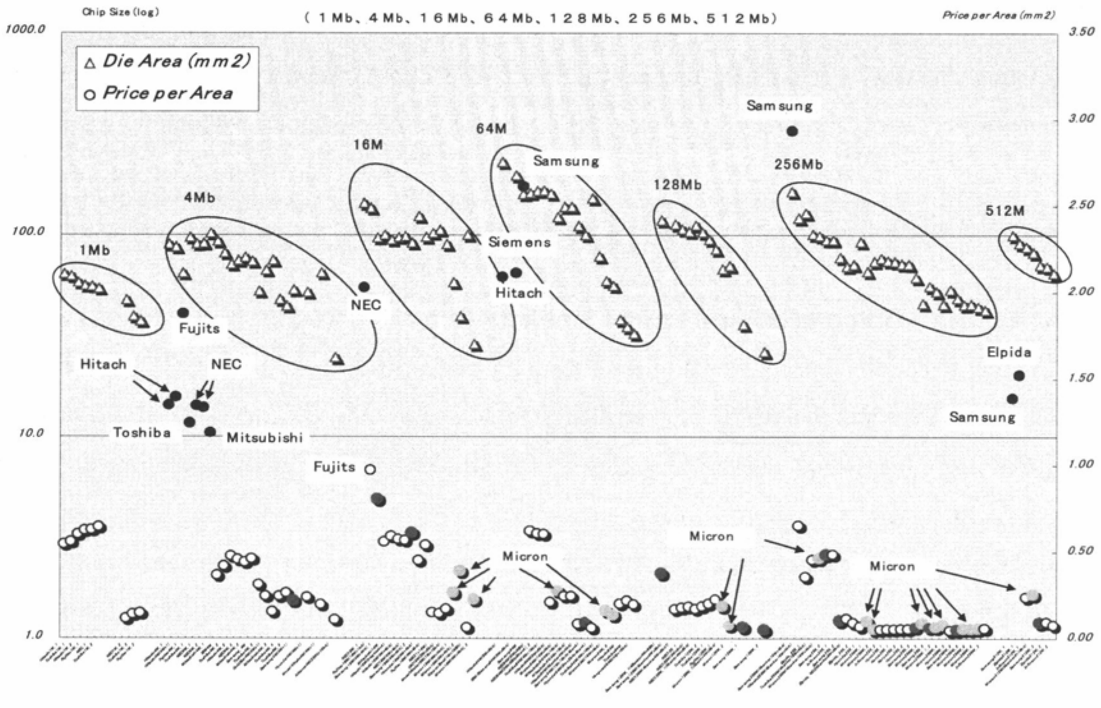
4.1 The situation between Scylla and Charybdis

The condition that the Japanese manufacturers lost not only profits from mass production but also profits as a leader for 64 Mb or larger DRAMs is shown in Figure 6. The vertical axis on the left side of this figure stands for the size of a DRAM chip (logarithm value) and that on the right side for the DRAM price per square millimeter. On the horizontal axis, a total of 145 mass-produced DRAMs were arranged according to the capacity and the year of manufacture. For example, in a certain circle clearly specified as 64 Mb in this figure, the 64 Mb DRAMs manufactured by each company are arranged according to the year of manufacture. Also, the △ sign within the circle stands for the chip-size. It can be confirmed that within this 64 Mb circle, the chip-size became smaller along with the elapse of the year.

Furthermore, the point indicated by the ○ sign in this figure stands for the price of these mass-produced products[14] which has been converted based on the unit of one square millimeter. There are few signs of ○ in the upper part but many in the lower part. And, as this means that the higher a ○ sign goes, the higher the price per millimeter is, it is possible to gain huge business profits. For example, in the case of the above 64 Mb DRAMs, there is a ○ signs filled with blue in the figure, and this stands for Samsung. From this it is known that in terms of the price per millimeter, Samsung occupied the most favorable position for 64 Mb DRAMs at the beginning.

[14] Refer to Semico Research (2003) for the price.

Figure 6: Transition in Chip Size and Price per Chip Area (Commercial Products)



In addition, Hitachi was the first manufacturer to launch mass-produced 64 Mb DRAMs to the market (in 1993) and next were Siemens and Samsung (both in 1995). In the figure, however, the prices per chip-size of Hitachi and Siemens were shown in a place slightly lower than the products manufactured by Samsung (look at the logarithm value). The reason for this is that, though Hitachi was the first to start mass production, the chip-size at that time was 229 mm^2 (and that of Siemens was 197 mm^2), considerably larger than Samsung's chip-size which was 159 mm^2.

Among the many ○ signs in the lower part of the figure, those filled with red stand for the price per millimeter of the DRAMs manufactured by Samsung and those filled with green stand for that of DRAMs manufactured by Micron. In order to easily identify these two companies, the price of DRAMs manufactured by Micron is indicated with an arrow. The white ○ signs in the part below these are the prices per millimeter of DRAMs made by the Japanese manufacturers.

Based on the data collected in Figure 6, we can observe a few interesting conditions as follows regarding mass-produced DRAMs from 1 Mb to 256 Mb.

- The Japanese manufacturers enjoyed both profits as a leader and profits from mass production for DRAMs from 1 Mb to 4 Mb.
- For 16 Mb DRAMs, Fujitsu, next to NEC, gained profits as a leader; however, during the first half of the period (1993-1994) Samsung, and during the second half (1996-1997) Micron enjoyed profits from mass production.

- (As was explained above) Hitachi took the lead in mass production of 64 Mb DRAMs but Samsung was able to gain profits as a leader till 1995, a year before DRAM prices drastically dropped. Moreover, initially (in 1996) there was room for Japanese players to secure profits from mass production, but after that they tended to be slightly depressed by Micron and Samsung.
- For 128 Mb DRAMs, in 1998 Samsung gained profits as a leader. In 1999, Japanese players, too, entered the competition but around 2000 they retreated one after another, with Micron and Samsung gaining significant profits from mass production.
- Even for 256 Mb DRAMs, too, Samsung which started mass production in 1998 gained profits as a leader. Regarding profits from mass production, Samsung and Micron repeatedly had a close contest with each other but Micron gained a slight advantage in the chip shrinking competition.

In this way, between Scylla and Charybdis, many of the Japanese manufacturers were driven to the bay in the market of 64 Mb or larger DRAMS.

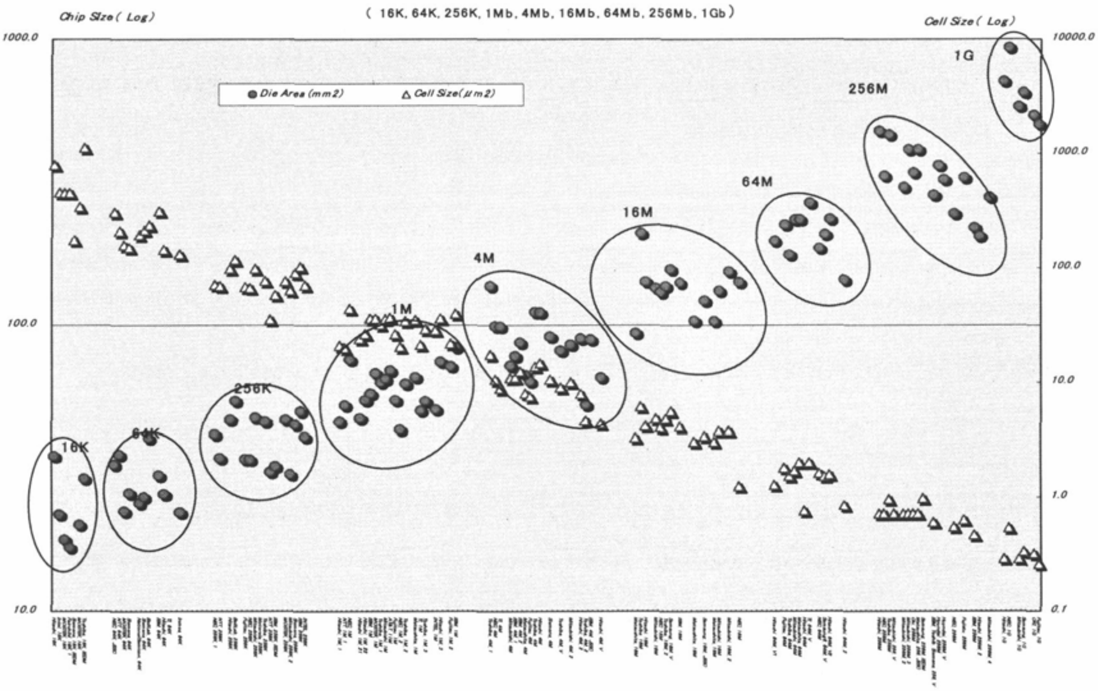
4.2 Declining speed of mass production: Impact of the insufficient marketing strategy

Although not mentioned in the previous section, Figure 6 further shows some noteworthy tendencies. One of them is that for 64 Mb or larger DRAMs, the capacity of the memory which had so far quadrupled in a manner like 64 Mb→128 Mb→256 Mb→512 Mb has been duplicated in a manner like 64 Mb→128 Mb→256 Mb→512 Mb. This new phenomenon has reflected not only the increasing technology complexity but also the rapid structural change in the semiconductor market, including the DRAM market, from the second half of the 1990s onward.

However, what will be discussed in detail in this and the next sections is that many of the Japanese manufacturers could not necessarily respond to such an unexpected change in the semiconductor market in a prompt enough way. One of the major reasons for this was their failure to succeed not only in the "integration of knowledge" among the R&D, manufacturing, and marketing and business divisions within the corporation, but also in the integration of knowledge by extending beyond corporate boundaries.

Judged from the marketing strategy, the Japanese manufacturers were forestalled in catching up with the turning point of the above-mentioned change from quadruplication to duplication (in 1997 and 1998). As a result, Samsung managed to gain profits as a leader from 128 Mb DRAMs, though it was still inferior to the Japanese manufacturers in terms of the research and development capability at that time. In reality, taking advantage of the brief moment when Japanese players were hesitant about making a clear-cut decision, Samsung jumped to the top as a firm seeking profits as a leader. To be more specific, it managed to start selling 128 Mb and 256 Mb DRAMs respectively in the first and second halves of the same year of 1998 (in the 8^{th} week of 1998: Model KM48S16030T-GL; in the 48^{th} week of 1998: Model KM44S64230AT-GL). Moreover, as is shown in Figure 6, even for the first mass-produced 128 Mb DRAMs, it launched the products with a chip-size as small as a little larger than $100mm^2$. That might really have been a boon from the Samsung-styled strategy of "simultaneity of marketing and development" (Chou (2007)). Incidentally, the chip-size of a 256 Mb DRAM manufactured by Samsung in late 1998 (KM44S64230AT-GL), too, was 164 mm^2.

Figure 7: Transition in Chip Size and Cell Size (Engineering Products for Development)



On the other hand, at the time of launching next-generation mass-produced DRAMs, a conventional view that "mass-produced DRAMs launched as a market leader are sellable even if the chip-size is somewhat larger" continued to exist among Japanese players' researchers and developers even in the 1990s. This can be inferred from the trend of specifications presented at ISSCC for DRAMs developed as next-generation products (refer to Figure 7). The right vertical axis of this figure stands for the chip-size and the left one for the cell-size. In addition, each ○ sign stands for the chip-size and the □ sign stands for the cell-size of the product developed by a manufacturer. The horizontal axis shows the names of the products presented by the manufacturers which are arranged according to the memory capacity and the year of presentation. In addition, for DRAMs from 64 K (1978-1981) up to 1G (1995-1996), Japanese players took the lead in all the cases according to the year of presentation.

As is known from this figure, the cell-size (□) had been shrunk at a certain speed according to

Moore's Law. On the other hand, in line with that trend, the chip-size, too, had been expanded by a certain value. In other words, the presentation of the products developed had been conducted at the imitative of the Japanese manufacturers under the "belief" that "the shrinking of the cell-size inevitably accompanies the expansion of the chip-size," To be specific, we can confirm the numerical values as follows: 197 mm^2 of Hitachi's 64 Mb in 1990, 186 mm^2 of NEC'S 64 Mb in 1992, 478 mm^2 of Hitachi's 256 Mb in 1993, 246 mm^2 of NEC's 256 Mb in 1996, 715 mm^2 of Hitachi's 1Gb in 1996, and 936 mm^2 of NEC's 1Gb. They are of a large size worthy of surprise nowadays, but this gives a glimpse into how competition for development was underway with nothing to do with mass production. However, after DRAM prices drastically dropped from 1996 onward, nearly no chips with a size larger than 100 mm^2 could exist as a mass-produced product any longer (refer to Figure 6).

All of the Japanese manufacturers except Hitachi successively started mass production of 128 Mb DRAMs approximately one year later than Samsung's start of its duplication strategy mentioned above. On the contrary, however, oversupply was incurred and 128 Mb DRAM prices dropped to approximately 50% in 1999 (0.15 dollars), to approximately 30% in 2000 (0.10 dollars), and to 7% in 2001 (0.023 dollars).Those were the years when the Japanese manufacturers successively retreated from the market: Fujitsu (in 1998), the foundation of Elpida (in 1999), Toshiba (in 2001), Mitsubishi Electric (in 2002), etc.

In addition, Hitachi eventually did not start mass production of 128 Mb DRAMs, though its true intention is unknown. Instead, it started to sell 64 Mb DRAMs with an extremely small chip-size of 38 mm^2 at the beginning of 1999. As the chip-size of the 64 Mb DRAM manufactured by Micron (MT48LC8M8A2TG-8EB) was 56 mm^2, Hitachi's product was as small as 68% of that. Moreover, included in this product was Hitachi's latest world-class technology for 256 Mb DRAMs (to be described below), such as HSG, CMP[15], the world's first application of tantalum oxidized film as the insulating film of the capacitor,[16] and the phase shift mask.[17]

Hitachi aimed at the 128 Mb DRAM market by bundling 16 such small chips, two times the conventional number, and packaging it as one memory module. However, Hitachi failed to make the best use of the sophisticated miniaturization and chip-shrinking technology incorporated in the most advanced product, due to negative factors such as the delay in the speed of expanding mass production, the rapid decline in 128 Mb and 256 Mb DRAM prices, and unexpectedly solid demand for products such as the existing 64 Mb DRAMs. And, if judged from the result, though having the top research and development capability in the world, Hitachi finally retreated from the

---

[15] Abbreviation of Chemical Mechanical Planarization or Polishing.

[16] A capacitor is an element to save electricity (electric charge) temporarily, and it is also called in Japan as a condenser.

[17] It depends on field research to Kawamoto, Matsuoka (1999), and the Hitachi affiliate.

market due to the unexpectedly drastic change in the structure of the DRAM market and its delay in responding to such a change, with the competitors taking advantage of a momentary chance.

4.3 Impact of the weakening production system

The above-mentioned structural change in the DRAM market was not influenced only by the devastating event of drastically declining DRAM prices in 1996. That was also seen in the fact that with this period as a boundary, the chip-size of MPUs (Micro Processor Unit) manufactured by INTEL and AMD, despite their rapid miniaturization, no longer increased when a certain value was reached (McClean Report (2006)). Behind such a phenomenon, the following structural factors concerning the whole semiconductor market had a significant impact.

(1) The rapid increase in the construction and operation costs of semiconductor factories (200 mm and 300 mm) and the costs of research and development to make full use of these factories
(2) The advent of the "era of PC" symbolized by Windows 95 which was put on the market in 1995 as the standard equipment for network functions, and along with that, a drastic increase in DRAMs loaded onto PCs (particularly from 1998 onward)
(3) The advent of low-end PC servers, and along with that, a growing degree of mixing of high-, middle- and low-price servers
(4) The advent of the Internet era with PCs and servers bundled together on a worldwide scale
(5) The full-scale emergence of digital consumer electronics symbolized by cellular phones and digital cameras
(6) The shortening of the DRAM life cycle along with the shortening of the life cycle of MPUs manufactured by INTEL
(7) A further accelerating decline in DRAM prices

All of these factors enhanced the importance of improving the efficiency of chip-size shrinking and factory operation (including the shortening of the cycle time and the reduction of inventory), and the early-stage yield (profitability).[18]

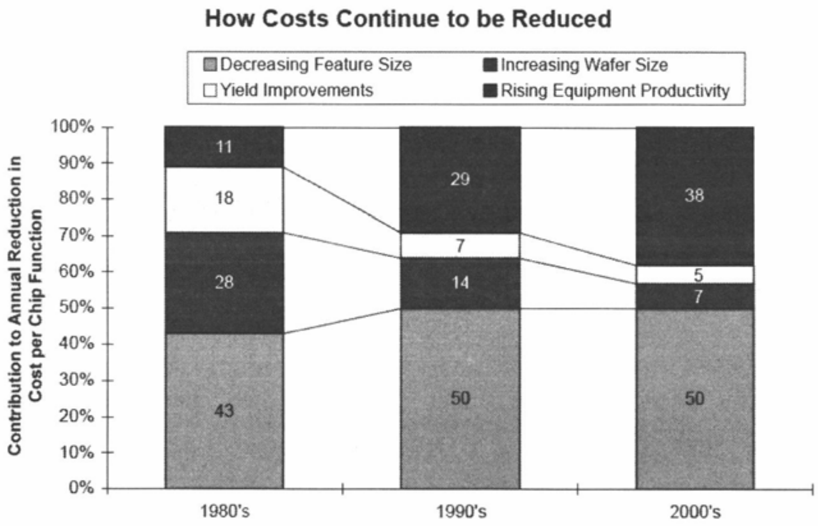
Regarding the semiconductor production system (normally referred to as factory integration),

---

[18] The specification of DRAM is greatly different in the memory capacity, the access speed, the I/O speed, and power consumption, etc. depending on the factor such as (3) and (5). In addition, because a high level and a middle class and a low-priced server had existed together, the semiconductor chipmaker's judging the period that turned on new generation DRAM became more difficult. As a result, the complexity of the market increased rapidly, and the necessity of the marketing strategy with a high resolution rose. Individual demand has enlarged rapidly in addition compared with the corporation demand. It pressed the huge expansion of the spot market, and increased the fluctuation risk and the indeterminacy of the DRAM market rapidly. This increased the importance of the business management that was able to correspond to the unexpected situation change quickly.

a certain sort of conventional view still existed persistently among many engineers. That is the conventional view holding: "The optimal production system *per se* differs between production with low mix and high volume (abbreviated as LMHV) and production with high mix and low volume (abbreviated as HMLV)," "The former is indispensable for DRAMs and the latter is indispensable for SOCs (System on Chip)," and "For the semiconductor production system till the 1990s when DRAMs constituted the core, the LMHV method was suitable but the HMLV method is not suitable." No doubt, compared to the LMHV method, a more sophisticated production system will be needed for the HMLV method. However, the Japanese style LMHV method (i.e., the so called push-type production method) in the 1990s is completely inappropriate as the production method for DRAMs nowadays. In reality, the above-mentioned conventional view itself, too, is considered as one of the factors that caused the delay in the speed of mass production.

Figure 8 Increasing Importance of Factory Integration and Chip Shrink



Source: Sematech, IC Insights

The shortening of the product life cycle makes DRAM prices drastically drop in a short period, despite the prices of advanced DRAMs. In reality, even after the drastic price decline in 1996, there frequently occurred cases where prices declined to one-half or one-third in one year. Consequently, along with the elapse of time, the opportunity cost rapidly rose. As a result, how a manufacturer can shorten not only the time of launching a new product but also the cycle time of mass produced products through a low level of WIP (Work In Process) became vitally important for securing profits as a leader. Moreover, as the opportunity cost drastically increased, to a great extent, the shortening of the cycle time became the determinant factor for the timing to launch a new product. It is because this has a significant impact on the latitude of the marketing strategy.

In addition, discontinuously increasing factory construction and operation costs and research and development costs along with miniaturization dramatically enhanced the importance for improving the yield of quality items per wafer and shortening the time to launch factories and new products. Cost reduction through chip-shrinking and efficient factory operations, too, became even more important. And for this purpose, too, the shortening of cycle time (regardless of trial products or mass-produced products) became important. This is because the shorter the cycle time becomes, the more frequent chances to learn within a certain time period will be available, thus leading to a high speed to achieve a high yield, a high chip-shrinking speed, and the accumulation of know-how of factory operation at an earlier stage. This tendency can also be confirmed in Figure 8. According to this figure, the degree of effective equipment utilization and the degree of chip-shrinking have come to determine a little less than 90% of the cost performance nowadays.

However, from the second half of the 1990s onward when such shortening of the cycle time had become considerably important, competitiveness of the semiconductor production system in Japan showed an apparent tendency to weaken (refer to Chuma (2007) for details). On the other hand, being conscious of the fact that its actual cycle time was ranked as the worst in the world in 1995, Samsung succeeded by making company-wide concerted efforts in shortening the cycle time for 64 Mb DRAMs to approximately 30 days by around 1998. Regarding Micron, information was even less available to outsiders concerning its production system. However, according to the authors who had the experience of personally acting as technical consultants to U.S. semiconductor manufacturers including Micron (Johnson *et al.* (1998)), Micron already had the efficient production system mentioned below in 1998.

> "Micron's strengths are that they have a captive, detail oriented, manufacturing workforce with a very high work ethic. Staff turnover is almost non-existent and loyalty is very high. Their production 'machine' is very efficient. Their style is almost like the Japanese in many respects with its high focus on quality and continuous improvement." (Page 19)

If a manufacturer was left behind by these two companies with a difference in the production system, it must have had great difficulties in making effective use of its research and development capability.

4.4 Impact of the weakening capability of science knowledge integration

Till the previous section, we confirmed the condition of Japanese players' insufficient marketing strategy and weakening production system. Even so, there still remains the doubt: if the Japanese manufacturers had maintained their overwhelming advantages in research and development concerning DRAMs, would the decline so serious as in the late 1990s perhaps not have been incurred? In this section, we want to examine this by further dwelling on the technical aspect. Below, in order to clarify this point, we will focus on the characteristics of the processing technology which constituted the key to 64 Mb or larger DRAMs. The reason for raising 64 Mb DRAMs predominantly is that since the advent of 64 Mb DRAMs, complexity of technology had rapidly increased and the DRAM technology of each manufacturer to cope with such complexity had become diversified. In reality, along with such rapidly increasing complexity, unavoidably the magnitude and depth of integrating knowledge within and outside the corporation expanded drastically.

A. Key processing technologies for 64 Mb DRAMs

For 4 Mb or larger DRAMs which appeared in the second half of the 1980s, among the processing technologies, the importance of the sophisticated technology concerning the capacitor[22] and the high-precision wafer-polishing technology using CMP (to be described below) rose discontinuously. Of course, rapid progress was made in transistor miniaturization according to Moore's Law. At that time, regardless of the types of devices such as MPU and DRAM, CMP became the key technology. However, the DRAM-processing technology faced one special situation. That is, even if a transistor is miniaturized, the capacitance required by the capacitor which is indispensable for storing binary information has hardly changed. Consequently, for mass production of 4 Mb or larger DRAMs, the molding of the capacitor had become the most difficult bottleneck for the processing technology. In reality, in DRAMs nowadays, the capacitor has become several times larger and more complex than the transistor.

Amid such a trend, the discoveries and inventions in Japan and the U.S., particularly those of the processing technology made by Hitachi, NEC and IBM, as will be described below, played an important role at the time of mass production (Tung *et al.* (2003)).

- Technology of making a 3-dimensional capacitor structure such as stack-type and trench-type capacitors to dramatically increase the capacitance of a capacitor (both by Hitachi)[19]
- Technology of dramatically increasing the capacitance of a capacitor by using tantalum oxidized film (T_aO_x) and BST (barium strontium titanate) which have a high permittivity (by Hitachi and Mitsubishi Electric, respectively)[20]

---

[19] One of the capacitors of the 3D construction is a stacked type piled on the transistor. Another is the trench type that ditches it to the substrate of silicon. Making the capacitor structure three dimensions was introduced into 4MbDRAM for the first time.

[20] The degree where the material where the electric charge is saved is called a high dielectric substance, and the electric charge is saved is called a relative permittivity.

- HSG (Hemispherical Silicon Grains)[21] technology of dramatically increasing the storable capacitance by making the superficial area of the electric conductor polysilicon (Si)[22] several times larger (by NEC)
- CMP polishing technology for dramatically flattening the wiring layer and the transistor layer (by IBM)[23]
- STI (Shallow Trench Isolation), a device isolation technology (using the CMP technology) of reducing mutual interference among the devices comprising a transistor and dramatically enhancing the transistor's controllability (by IBM)

Table 3: Transition in the Year of Introduction of Key Process Technologies and Their Applied Commercial DRAM Products

Key Process Technology	1991	1992	1993	1994	1995	1996	1997			1998	1999	2000
Structure of Stacked Capacitor			3-Fin type COB			Multi-Layerd Polysilicon COB	Crown (polysilicon) COB	Crown (textured polysilicon) CUB	Stacked (textured polysilicon) COB	Stacked (textured polysilicon) COB	Stacked (textured polysilicon) COB	
			○			○	○	○	○	○	○	
			Hitachi (64Mb)			NEC(64Mb)	Hitachi (64Mb)	Micron (64Mb)	三菱電機 (64Mb)	Samsung (64Mb)	Hitachi (64M)	
HSG								HSG COB		HSG COB		
								○		○		
								NEC(16Mb)		NEC(64Mb)		
Structure of Trench Capacitor					TRC (Trench Capacitor)	BPT (buried plate trench)						BEST (buried strap
					○	○						○
					SIEMENS (64Mb)	Toshiba (64Mb)						Toshiba (64Mb)
Capacitor (high-k) Dielectric											Tantar Oxide (TaOx)	
											○	
											Hitachi(64Mb)	
CMP	Interconnect Layers				Interconnect & Transistor Layers(STI)	Interconnect & Transistor Layers(STI)	Interconnect Layers、First for Stacked Capacitor			Interconnect & Transistor Layers(STI)、first for Stacked Capacitor	Interconnect & Transistor Layers	
	○				○	○	○			○	○	
	IBM (4Mb)				SIEMENS (64Mb)	Toshiba (64Mb)	Micron (64M)			Micron (64M)	Hitachi (64M)	

Sources: Chipworks, Semiconductor Insights, http://smithsonianchips.si.edu/ice/s4.htm, Tatsumi et. al. (2002) and Interviews

Note1) COB= Capacitor Over Bit Line, CUB= Capacitor Under Bit Line

Table 3 shows when these critical technologies were introduced for mass production of 64 Mb DRAMs by the Japanese, U.S., South Korean and European manufacturers. In this table, the first row shows the above-mentioned major processing technologies and the first line shows the particular year when each of these technologies was introduced. In the three columns corresponding

21 When other conditions are assumed to be constant, an electric charge that the wider the surface area of the conductor is, is the bigger can be saved. The HSG technology is a technology that is rugged of the surface of the conductor and rapidly enlarges the surface area.

22 The capacitor is a structure to place the insulation film between conductors. A lot of groups of the atom that queues up regularly in various spacings (crystal grain child) exist in the polycrystalline though the atom aligns regularly mutually in single crystal.

23 When other conditions are assumed to be constant, an electric charge that the wider the surface area of the conductor is, is the bigger can be saved. The HSG technology is a technology that is rugged of the surface of the conductor and rapidly enlarges the surface area.

to each particular technology, the upper column indicates the name of the technology's revised version, the ○ in the middle indicates the time when the technology started to be used, and the lower indicates the name of the semiconductor manufacturer which introduced the technology.

B. Delay in mass production of HSG technology

As is shown in the second row of Table 3, the HSG technology was introduced for full-scale mass production of 64 Mb DRAMs in 1998 by NEC which was the first developer of this technology. Nevertheless, as is shown in the first row, the mass-produced 64 Mb DRAMs with textured[24] capacitors, which were DRAMs closely resembling HGS, were put on the market by Micron and Mitsubishi Electric in 1997 and by Samsung in 1998. However, if compared by means of 20,000x electronic microscope photographs, among the three manufacturers, the textured shape of the DRAMs manufactured by Micron was the most fine-featured and clear-cut. Also, capacitors manufactured by Samsung, too, though not so good as those manufactured by Micron, were of a clear textured shape. On the other hand, regarding capacitors manufactured by Mitsubishi Electric, the textured shape cannot be discerned so clearly by means of 20,000x electronic microscope photographs. The same thing can be said regarding capacitors manufactured by NEC in 1996, too. Therefore, in 1998 NEC, Micron and Samsung were the three manufacturers which applied HSG to mass production to a considerable extent.

Regarding the reason why NEC lagged (relatively) behind in HSG mass production, some published data gives us an important hint. NEC applied for a Japanese patent on HSG in 1989 (registered in 1996) and applied for a U.S. patent (5366917) in 1994 (registered in 1994). In addition, the initial HSG-related presentation at IEDM, too, was made by NEC in 1990. However, Micron applied for a U.S. patent on the HSG-related technology (5037773) ahead of NEC in January 1990. Moreover, the presentation at IEDM, too, was made at the same session as NEC in December 1990. On top of that, in July 1990 before the presentation at IEDM, Micron also published an academic paper on IEEE Electron Device Letter, in which it raised the above patent as reference literature.

The HSG-related U.S. patent application and the presentation at IEDM were made mainly by Pierre Fazan[25] (who received a Ph.D. of Physics from the Swiss Federal Institute of Technology in Lausanne in 1989). As it was in 1989 that he joined Micron, both the patent application and the presentation of the academic paper were made at an exceptionally high speed. All of his research papers before he joined Micron were about the capacitor, and there were three papers published in

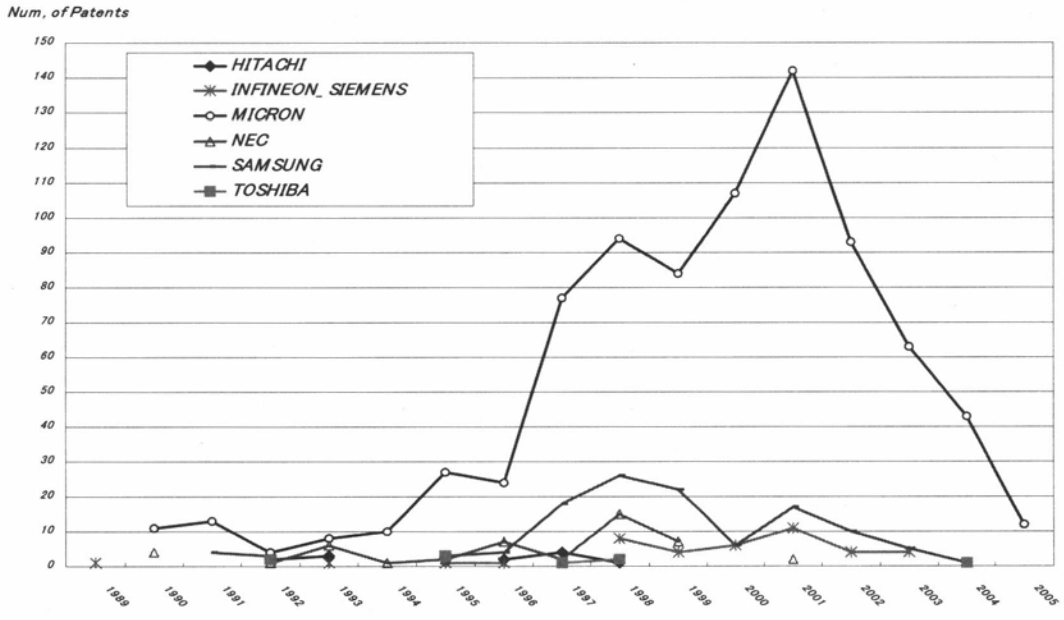
[24] The capacitor of the HSG (hemispherical grain) structure is called "Textured", "Texturing", "Rugged", and "Modulated stacked" (Tung, Sheng and Yuan (2003)).

[25] Dr. Fazan is an inventor of ZRAM (Zero-Capacitor DRAM) that is stealing the limelight as an innovative memory technology currently. Reference at IEEE Spectrum January 2006 issue "Winners & Losers", too.

magazines like *Solid-State Electronics* in 1987 (for two of which he was the first author).[26] Therefore, it can be easily imagined that Fazan himself was an excellent researcher and developer at that time. However, if judged from the fact that he received his Ph.D. in 1989, it can be known by analogy that at least regarding HSG, he was still in the stage of knowledge utilization but not knowledge creation in 1990.[27]

Well then, how did Micron create and utilize HSG-related knowledge? The profile of the co-authors of Fazan's IEDM-related academic papers from 1990 to 1995 gives us an answer (refer to Table 4). From this table, it can be inferred how Fazan and his colleagues in Micron carried out research and development along with the high-k material experts from the Austin Campus of Texas University and how RAM Research Corporation, a semiconductor equipment manufacturer, too, was involved. Also, there were three people who joined Micron after receiving a Ph.D. from Texas University (as far as we know). And many of the engineers who participated in the project joined Micron around 1990.

Figure 9: Number of US Patents Related to HSG Technologies by Application Year



Furthermore, until recently, Micron has registered 823 U.S. patents concerning HSG, a number overwhelming other HSG-related companies in the same industry. That condition is shown through the time series trend as well (refer to Figure 9).[28] What is interesting in Micron's HSG-related

[26] It retrieves it with Science Direct etc.

[27] At that time, the Lausanne Institute of Technology in Switzerland was researching the leading edge concerning the capacitor according to the specialist in this field. It depends on field research to the major semiconductor chipmaker designer.

[28] The patent related to HSG of Elpida and Renesas is one digit level. Therefore, even if various patents are being

patents is the characteristics of the top ten patent inventors. They were involved in 694 patents (84% of the total patents) but three of them originally worked for IBM. In addition, four other Micron employees who were involved in development with Fazan belonged to the top ten. And the remaining three Micron employees, too, attracted attention for their joint patent applications and joint presentation of academic papers at IEDM with IBM researchers who had strong associations with Micron. Such a trend can be seen also for the CMP-related patents to be dealt with in the next section. This gives us a glimpse into the deep relationships between Micron and IBM.

Then, what strategy did Samsung adopt? In order to know that, we made a comparison through the number of inventors ("number of researchers") collected and added without any overlap over all the years. The "number of researchers" was 126 in Micron. On the other hand, in the case of Samsung, the number of U.S. patents was 119, one-eighth of Micron's, but the "number of researchers" was 186, reaching 1.5 times that of Micron's.[29] Therefore, in Samsung the person with the largest number of invention patents had 12 patents while that in Micron had 140 patents, which is a significant difference. Furthermore, Samsung's application for HSG-related U.S. patent (5134086) was made in October 1991, which was a very early stage. From these facts we can see the Samsung-styled strategy to "promptly create and utilize knowledge by mobilizing a large number of researchers and developers." This is notable also regarding CMP to be dealt with in the next section.

At the same time, NEC had 47 U.S. patents (with "number of researchers" as 32) and Hitachi had 15 U.S. patents (with "number of researchers" as 36), and the HGS-related number of HSG-related patents and "number of researchers" of both manufacturers were one-digit smaller than those of Micron and Samsung. On the other hand, Hitachi applied for an HSG-related U.S. patent (5444302) in December 1993, over one year later than Samsung. In this regard, there is a high possibility that Hitachi's so-called NIH (Not-Invented-Here) syndrome may have occurred.[30] To be frank, if there is such a huge gap in the number of developers, there is also a possibility for Hitachi and NEC to have been inferior to Micron and Samsung in the speed of HSG mass production.

In addition, NEC reached an agreement with Samsung on 256 Mb DRAM cells in February 1994, and further reached an agreement on joint research of manufacture technology in March 1996 (*Nikkei Keizai Shimbun* dated March 20, 1996). As a result, the mutual exchange of researchers and developers was implemented almost once a month. Also, according to Mathews and Cho (1999), p.137, joint research was conducted in the same way regarding 16 Mb/SDRAMs, too. Furthermore,

---

transferred to both companies by Hitachi and NEC, the influence can be almost disregarded.

[29] Therefore, the person whose number of invention patents is most in Samsung is 12. However, the person whose number of invention patents is most in Micron is 140.

NEC concluded a contract with Micron on sales and production tie-ups in the first half of the 1990s and carried out the mutual exchange at the level of researchers and developers. Therefore, we cannot rule out the possibility either that compared to other manufacturers in the same industry, these tie-ups may have accelerated the spillover to Samsung and Micron which boosted their strong personnel as described in the above.

C. Delay in the mass production of CMP technology

The CMP technology is well known as a technology which IBM had kept under lock and key since the early 1980s. IBM first presented its usefulness at IEDM in 1989.[31] IBM provided Intel with this precious CMP technology in 1987 and granted a cross license to Micron in 1988. (Perry (1998)). According to IBM's historical records, IBM started joint research and development with Micron concerning the memory in the same year.[32] This is also an anecdote attesting the strength of an aspiration for national unity among U.S. semiconductor manufacturers under the Japan-U.S. agreement on semiconductor trade, and Micron's first class capability to utilize knowledge (to be described below).[33]

Before the CMP technology was introduced, the flattening technology requiring considerable dexterous skills was indispensable (in particular, Spin-on Glass (SOG) and Resist-Etchback (REB) technologies). However, with the introduction of CMP, such skills became unnecessary. In addition, the fact that an ideal flatness could be achieved through CMP brought about significant advantages to aspects other than manufacture. One of them is that it had become possible to divide the processing technology into more detailed modules. As a result, latitude in design and manufacture was dramatically enhanced (Sunami (2006)).

In addition to that, not only did things like ideas needed to realize a special logic circuit with fewer transistors become increasingly obvious, but it became easier for them to be hatched as well. Also, as it was easy to theorize the interdependence between modules, it had become possible to conduct more precise simulation. As that accelerates the speed to identify and solve problems and lead to more chances to learn within a certain period of time, as a result, it is possible to enhance

---

[31] Moreover, when IBM began the R&D of the CMP technology in the early 1980's, Japanese researcher in IBM, Dr. Ogura (Ogura Seiki, from the faculty of science and engineering, Waseda University) played a leading role. This information comes from Dr. Koyanagi of Tohoku University who invented the stack capacitor while serving Central Research Laboratory, Hitachi Ltd.). Dr. Ogura reduces hot electron (hot-electron) effect (degradation phenomenon of disorder etc. of the transistor threshold that the hot electron causes) in dramatic form and is famous as the person who invented the LDD (Lightly Doped Drain) technology that improves controllability of the transistor. LDD has been introduced from 1MbDRAM as an indispensable technology.

[32] Refer to http://www-03.ibm.com/ibm/history/history/year_1989.html and Perry (1998). Ms. Perry is a CMP developer of former IBM and has held a crucial position successively with Semiconductor Manufacturing Technology Institute, Motorola, Applied Materials, and Cabot, etc. afterwards (http://www.cabotcmp.com/investor_news/10k.pdf).

[33] IBM applied this CMP technology to the mass production of 4MbDRAM for the first time in the latter half of the 80's. The one that concerns this 4MbDRAM is included in one of the analytical reports (Semiconductor Insights) used by this paper.

the yield through a shorter learning period. In this way, the introduction of CMP brought about extensive external effects.

The fourth row of Table 3 shows each manufacturer's condition of introducing the CMP technology for mass production. According to this table, at least till the end of the 1990s, with Toshiba's alliance with IBM as an exception, the Japanese manufacturers all delayed introducing the CMP technology. In reality, in the case of Hitachi, as was described in the above, CMP was first introduced for the purpose of applying it to 64 Mb DRAMs of 1999 into which a variety of the latest technologies were incorporated. [43] On the other hand, as is shown by Table 3, as a start, Micron applied CMP to the wiring layer of mass produced 64 Mb DRAMs of 1997. And in 1998, it applied CMP also to the transistor layer for mass production. Moreover, Samsung and the Japanese manufacturers realized the above-mentioned device isolation technology of STI (Shallow Trench Isolation) (IBM) for 256 Mb or larger DRAMs.[34]

Table 7: Research Collaboration in CMP-Related Tech. by Given-& Own-Name Matching in US Patents

Hitachi			
同名相手企業名	同名発明者数	発明者名	特許出現頻度
Texes Instruments	8	ASANO; ISAMU	32
		ENOMOTO; HIROYUKI	4
		KAERIYAMA; TOSHIYUKI	6
		NISHIMURA; MICHIO	7
		SUKEGAWA; SHUNICHI	2
		TSU; ROBERT	5
		YAMAZAKI; KAZUO	3
		YASUDA; MASAYUKI	2
Toshiba	2	ABE; MASAHIRO	6
		AOKI; HIDEO	17
NEC	2	WATANABE; KENJI	3
		YOSHIDA; MAKOTO	18
Ebara	1	WATANABE; KENJI	4
Shinetsu	1	KOBAYASHI; MAKOTO	3
合計	14		112
NEC			
TOSHIBA	3	HAMAMOTO; TAKESHI	5
		HAYASHI; KAZUHIKO	7
		SEKINE; MAKOTO	6
HITACHI	2	WATANABE; KENJI	3
		YOSHIDA; MAKOTO	18
EBARA	1	WATANABE; KENJI	3
MICRON	1	DRYNAN; JOHN M.	12
SUMITOMO	1	TAKASHIMA; MASAYUKI	3
合計	8		57
Samsung			
INFINEON	2	KANG; WOO-TAG	6
		KIM; WOOSIK	2
IBM	1	SIM; JAI-HOON	2
INTEL	1	LEE; JONG-WON	11
合計	4		21

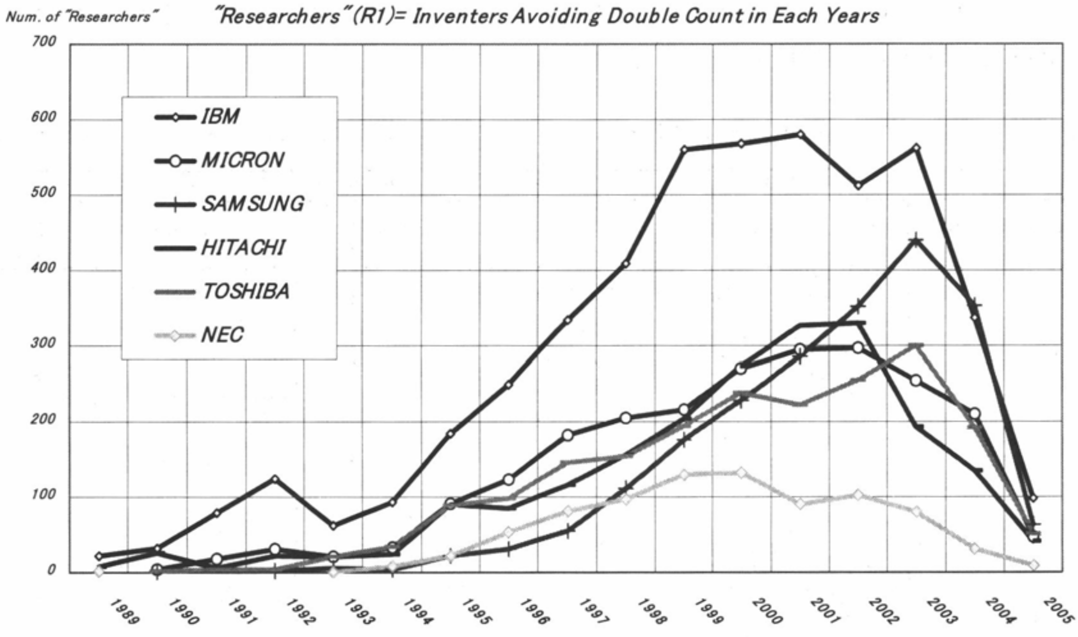
Micron Technology			
同名相手企業名	同名発明者数	発明者名	特許出現頻度
IBM	6	BHATTACHARYYA; ARUP	18
		FARRAR; PAUL A.	72
		GIVENS; JOHN H.	40
		JOST; MARK E.	21
		NOBLE; WENDELL P.	116
		PAN; PAI-HUNG	38
INTEL	3	DENNISON; CHARLES H.	114
		LOWREY; TYLER A.	64
		SHARAN; SUJIT	35
MOTOROLA	6	BROWN; NATHAN R.	8
		KIM; SUNG C.	7
		KIRSCH; HOWARD C.	4
		MANZONIE; ADAM	3
		YU; CHRIS C.	24
		ZHU; THEODORE	13
Texas Instruments	7	CHO; CHIH-CHEN	10
		KWOK; SIANG P.	4
		LARSEN; JODY D.	4
		RICHARDSON; WILLIAM F.	3
		VISOKAY; MARK	7
		WU; ZHIQIANG	33
		ZIELINSKI; EDEN	3
NEC	1	DRYNAN; JOHN M.	12
RODEL	1	MANZONIE; ADAM	3
CABOT	1	YU; CHRIS C.	16
APPLIED	3	DOAN; TRUNG	10
		ROBINSON; KARL M.	91
		THAKUR; RANDHIR P. S.	61
NOVELLUS	1	SMITH; DAVID	2
SPEEDFAM	2	GRIEF; MALCOLM K.	7
合計	31		843

The speed of applying CMP to mass production like this can be known even from the huge development recourses injected into CMP by Micron. For example, (until recently) the number of CMP-related patents registered by Micron (3133) rose by 50% above the 2,030 patents held by

[34] the achievement of STI that uses CMP by IBM is 16MbDRAM.

IBM, the birthplace of the CMP technology. Also, what is interesting for knowing how this manufacturer has been utilizing knowledge is that among Micron's top ten inventors related to CMP, actually seven were estimated to have come from other U.S. and European manufacturers (such as IBM, Philips, Intel, Mostek and Kodak).[35] Furthermore, two Micron employees among the top ten, who were reasoned by analogy to have no work experience at other manufacturers (both of them received a Ph.D. from State University of Ohio), frequently carried out joint inventions and joint research with other developers of the top ten and those who came from IBM and Motorola or Applied Materials. Such a situation can be more vividly confirmed in Table 7.[36]

Figure 10: Number of CMP-Related "Researchers" (R1) by Original Application Year



Of course, (in both the prior and retroactive sense) as a comparison of the research and development capability, comparing by using the number of patents has a bias. This is because in many cases, there will be a great difference in the number of co-inventors per patent and the number of claims depending on a company's policy. Figure 10 takes account of such a bias and shows the change of each manufacturer by using, instead of the number of patents, the number of inventors (referred to as the "number of researchers") without any overlap in each year. According to this figure, the "number of researchers" of Micron is nearly half of IBM's but except for IBM,

[35] The fact to which the patent was registered by these semiconductor chipmakers has been used before inventors concerned registered the patent in Micron. In addition, did the utilization of the Internet information.

[36] First of all, the inventors of the patent related to CMP of each company were specified for making this table. Next, the inventors of the other companies (other semiconductor chipmakers and equipment makers and raw material makers) as which name was the same were made to match them with them. The disorder of the wording by nickname and the middle name, etc. was avoided by making the dictionary as much as possible. However, note that errors are still included.

Micron always occupied the top position in the 1990s. Investigation of Micron through the "number of researchers" is notable.[37]

Among the Japanese manufacturers, Toshiba which formed an alliance with IBM in the early 1990s had a large "number of researchers." However, around the late 1990s, Hitachi, too, put in battle formation its research force which was in no way inferior to Toshiba. Samsung, too, increased its "number of researchers" related to CMP from 1996 onward and in 2002 it came to boast a research force which was second only to IBM. What constituted a contrast to this is NEC. In particular, from 1998 onward when NEC was surpassed by Samsung in terms of the "number of researchers," its "number of researchers" was considerably small if compared to the level of other manufacturers in the same industry. Moreover, the number did not increase even after that and turned to decline after reaching the peak in 1998.

NEC's low level of development resources is more clearly reflected through the difference in the "number of researchers" without any overlap caused by the carryover to the next year, as was defined above. In reality, NEC's CMP-related patents numbered 729 but the "number of researchers" was 463. On the other hand, Samsung's patents numbered 1,019 and the "number of researchers" was 1,017, more than two times that of NEC. In the case of Hitachi, its patents numbered 606, fewer than NEC, but the "number of researchers" was 925, almost the same as Samsung. The interesting fact is that NEC's "number of researchers" was almost the same as 485, the "number of researchers" of Micron which boasted twice as many patents as NEC. Therefore, compared to other manufacturers, the same researchers and developers in Micron applied for a large number of patents each year. Micron's stance of giving more priority to utilization than to creation of knowledge was highlighted here, too. Of course, Micron compensated for such a low level of the "number of researchers" through joint inventions and joint research and development with other manufacturers' researchers and developers.[38] In the case of NEC, at least as far as IEDM papers and Japanese and U.S. patents are concerned, it showed a strong tendency to do everything on its own for both research and development. This is thought to have been the contributing factor to limit NEC's speed of mass production along with its delay in the introduction of the CMP technology.

---

[37] When "Number of researchers" is used, an overwhelming difference between Micron and the other companies of patent numbers that are one digit more than the other companies is lost. In Micron, a lot of R&D people have been overwhelmingly putting out a lot of patents compared with the other companies. For instance, there are eight people who have put out the patent related to 100 CMP or more in Micron. However, such one inventor is in IBM.

[38] When "Number of researchers" is used, an overwhelming difference between Micron and the other companies of patent numbers that are one digit more than the other companies is lost. In Micron, a lot of R&D people have been overwhelmingly putting out a lot of patents compared with the other companies. For instance, there are eight people who have put out the patent related to 100 CMP or more in Micron. However, such one inventor is in IBM. For instance, a top inventor of a related patent of the entire DRAM, CMP, and HSG is Mr. Leonard Forbes (IBM→HP→ University of Oregon) in Micron. The patent related to DRAM to which he or she who makes Micron a patentee is related reaches about 450. Moreover, high-ranking ten inventors' addresses are also variegated with NY state, Oregon state, and California state, etc. for a long term.

D. Technological Dominance of Tantalum Oxide Film Technology by Hitachi[39]

As is showed by Table 3, Hitachi was the first manufacturer to use the tantalum oxide film acid as capacitor insulating film in 1999. After that, for a short while Hitachi boasted an advantage which allowed almost no other manufacturers to follow suit. In reality, nowadays the tantalum oxide film and HSG are the critical technologies underpinning the competitive edge of Elpida, the only DRAM specialized manufacturer in Japan jointly established by Hitachi and NEC. Samsung is said to have undergone hardships in making full use of the tantalum oxide film. For that reason, for the most advanced 512 Mb or larger DRAMs, Samsung, ahead of the other manufacturers in the same industry, turned straightforwardly from the tantalum film and silicon nitride film which were a standard processing technology to the hafnium-series capacitor insulating film (Al2O3-HfO2)40 for which ALD (Atomic Layer Deposition) was used (Hashimoto (2004)).

A technological advantage of Hitachi remarkably appears to the number of patents related to the capacitor insulation that include ones related to tantalum oxide dielectric film and "number of researchers" (= number of inventors whose names do not overlap over the entire years). Certainly, the number of those patents by Micron is 649, and exceeds 168 of Hitachi. However, "the number of researchers "of Hitachi goes up to as many as 311 people, in contrast to the "number of researchers" 148 of Micron. On the other hand, Samsung's number of those patents is 84, and the "the number of researchers" is110 people. About NEC (NEC Electronics is included), there are 116 patents and 78 "researchers." These facts indicate the technological superiority of Hitachi concerning the high-k film.

5. Summary and Implications

In the science-based industries, the complexity of technology and the market increases rapidly. People who create the science knowledge and ones who use it tend to specialize in and be inevitably divided into each area. This paper especially analyzed the semiconductor industry among such science-based industries. And, by analyzing the ups and downs process in the DRAM business of Japan chipmakers, it was pointed out that the competitiveness of this industry crucially depended on the success or failure of organizational innovation within or beyond corporate boundaries that

---

[39] Here we do not deal with trench capacitor technology. This is related to the following a little bit complicated situation. The trench-type capacitor was adopted for 4 Mb or larger DRAMs only by IBM, Toshiba and Siemens. Moreover, in the early 1990s these three manufactures once formed a close alliance, with the CMP technology applied to IBM's 4 Mb DRAMs at the core in particular, and developed and mass-produced 64 Mb DRAMs (IBM and Siemens) and 256 Mb DRAMs (IBM and Toshiba). As a reflection of this, the electronic microscope photographs of the Siemens-manufactured DRAM in 1995 which we examined bore IBM's mark, and that of the Toshiba-manufactured DRAM in 1996 bore Toshiba's mark and the marks of IBM and Siemens. Therefore, there was almost no difference in the processing technology introduced into mass-produced DRAMs among Japan, the U.S. and Germany. However, what Siemens (its DRAM company was Infenion and is currently called Quimonda) did one year earlier is considered to have reflected the fact that it started to form an alliance with IBM earlier than Toshiba.

[40] The high-k insulation film with the stratified structure of hafnium oxide (HfO2) and aluminum oxide (Al2O3) has an electrostatic capacity that is higher than the tantalum oxide dielectric.

could organically tie together those two kinds of people specialized in knowledge creation or utilization.

The Japanese semiconductor industry rapidly dropped the share though still retained the advantage in R&D after the unexpected collapse of the DRAM price occurred in 96. One of those causes includes the insufficiency of intra-firm "synchronization in information" among divisions of R&D, manufacturing, marketing, and sales, etc. Moreover, such a limitation symbolically appears to the fact that many of Japanese semiconductor chipmakers misread the drastically changing phase that the capacity of DRAM that has quadrupled up to 64Mb came to be duplicated after that. In addition, the popular belief of the R&D people in "Early mass-produced goods sell even if the chip area was a little large" existed strongly in the backdrop of such misreading. It is because the actual feeling of marketing and sales divisions was not easily transmitted to the R&D division.

Such insufficiency of intra-firm synchronization was caused between various divisions of R&D, marketing, sales, and manufacturing. Actually, for example, the importance of reducing WIP (Work in Process) and shortening cycle time has risen rapidly in the DRAM market in the latter half of the 90's. However, a lot of Japanese semiconductor chipmakers kept persisting in a conventional push type production method up to the end of the 90's. The slowdown of the cost reduction motivation by having kept retaining a conventional standard full costing method also strongly affected such a situation. The weakening competitiveness of such a production system has decreased *ex ante* and *ex post* flexibility in the business management. It became even a cause that the advantage on R&D at that time does not effectively lead to the increase of the competitiveness in the products market.

The slowdown of the speed from development to mass production in Japanese semiconductor chipmakers had been strongly restricted also by the complexity spurt of process and design technologies that had been symbolically shown in 64Mb DRAM. It is because the complexity spurt of these technologies made it considerably difficult to promptly integrate, within each chipmaker, those technologies indispensable for mass-production. To clarify this point, this paper examined in detail when and by which chipmaker important process technologies like HSG, CMP, and the tantalum oxide (dielectric) film, etc. applied for the first time to the mass production of 64Mb DRAM. It was also confirmed that Micron and Samsung had surpassed even Hitachi at the mass production speed who was the leader of the knowledge creation type.

Micron executed intimate joint R&D with IBM over a long period of time, and procured excellent skilled R&D engineers from the outside. In other words, it excelled in "Technology marketing" even at that time. In addition, a large amount of R&D human resources were turned on about HSG and CMP. Samsung positively recruited top-class personnel who returned home from U.S., and turned on the R&D human resources of an overwhelming number that considerably exceeded Micron for HSG and CMP. On the other hand, Hitachi and NEC's tendencies to stick to the procurement of human resources within each company were strong. The input to HSG and CMP of the R&D human resources was also far fewer than that of Micron and Samsung. Additionally, the introduction of CMP technology was considerably delayed in both Japanese chipmakers compared with Micron. As a result, the mass production utilization of key process technologies invented by themselves was delayed. In addition, the R&D human resources had been considerably insufficient for all of HSG, CMP, and the tantalum oxide film technology in NEC since the latter half of the 90's. Micron and Samsung, however, were not able to catch up, for several years, the tantalum oxide film technology invented by Hitachi due to the difficulty of physical phenomenon involved in this technology. Hitachi did its mass production application in 1999. This technology has been also one of the key technologies of present Elpida together with the HSG technology invented by NEC.

Now, the semiconductor industry that has rapidly promoted miniaturization according to Moore's Law has been facing the difficult problem of responding to a rapidly diversified potential demand by making good use of various complex process and design technologies. The main cause of the difficulty comes from the phenomenon of "Demand Hiddenness"[41] that has been becoming rapidly remarkable. Moreover, such a difficulty is increasing furthermore because of the diversification of people's preferences and the globalization of semiconductor markets. In the situation with remarkable Demand Hiddenness, chipmakers have to attempt a continuous and frequent synchronization in information among not only between of suppliers and users but suppliers and users' users or more. In addition, the device like ASSP (Application Specific Standard Product) and the device like FPGA (Field Programmable Gate Array) increase in importance in the semiconductor market after 2000. ASSP can lag the decision up to immediately before actualizing users' demand, while FPGA can be supplied at once after potential demand is actualized. In a word, the demand for various semiconductor devices that have ex ante and ex post flexibility increases rapidly.

In such a situation, many of Japanese semiconductor chipmakers still cannot belong to the leading group in the SOC (System On Chip) markets after it withdrew from the DRAM business. The delay in intra- and inter-firm synchronization in information, the speed of collaborative science knowledge creation in various research consortia in Japan, and the speed of response to users' demand all over the world. These factors that inevitably induced the decline of the DRAM business in Japanese chipmakers have been blocked still greatly.

---

[41] Suppliers cannot learn the utility of its own various products by himself, while users do not learn themselves wanting it by themselves either. Such a phenomenon is called Demand Hiddenness.

References

- Chang, Hyku-Jun (2007), Research on Korean Semiconductor Industry: Mainly based on the Case of Samsung Electronics, MBA Workshop Report, Hitotsubashi University, Mimeo.
- Chuma, Hiroyuki (2006), "Increasing Complexity and Limits of Organization in the Microlithography Industry: Implications for Science-Based Industries," Research Policy, Volume 35, Issue 3, pp. 394-411
- Chuma, Hiroyuki (2007), "Search for Contributing Factors of Weakening Competitiveness of Japan's Semiconductor Production System: From the View Point of Papert's Principle," Cognitive Science, special issue, to be published shortly
- Integrated Circuit Engineering（ICE）Corporation (1997), *Cost Effective IC Manufacturing 1998-1999*, http://smithsonianchips.si.edu/ice/cd/CEICM/title.pdf
- 2003, Report Number VM113-03.
- JEITA（2003）、『IC Guidebook —2003 Version— A Full View of Semiconductor Industry and Technology Which Open up the Trend of the a New Era』.
- Johnson, C., Ron Leckie, Paul Buddendorff, John Fisher, and Fred Holstein (1998), "Special Report: Micron at the Crossroads, " Infrastructure, May 28,
- Leachman, R. and C., Hodges, D. A. (1996), "Benchmarking Semiconductor Manufacturing," IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING, vol.9, no.2, pp.158-169.
- Macher, J.T., D.C. Mowery and D.A. Hodges (1998) "Reversal of Fortune? The Recovery of the U.S. Semiconductor Industry," California Management Review 41(1): 107-136.
- *McClean Report (2006)* , Semiconductor Insights,
- Mathews, John A. and Dong-Sung Cho (2000), *Tiger Technology: The Creation of a Semiconductor Industry in Asia*, Cambridge University Press.
- Minsky, L. M. (2006), *The Emotion Machine: Commonsense Thinking, Artificial Intelligence, and the Future of the Human Mind*, New York: Simon & Schuster.
- Minsky, L. M. (1986), *The Society of Mind*, New York: Simon & Schuster.
- Ohyane, Satoru (2002), "Semiconductor Conflict between Japan, U.S. and South Korea: Political Economics of Trade Negotiations," Yushindo
- Perry, K. A. (1998), "Chemical Mechanical Polishing: The Impact of a New Technology on an Industry," Symposium on VLSl Technology Digest of Technical Papers (Invited), pp.2-5
- SEMICO Research（2003）、"DRAM by Design: Comprehending DRAM Life Cycles," July
- Tung, Chih-Hang, Ceorege T. T. Sheng and Chih-Yuan Lu (2003), *ULSI: Semiconductor Technology Atlas*, John Wiley & Sons, Hoboken, New Jersey.
- Sunami, Hideo (2006), "Adopt New Materials and Structures to Break down the Barrier of

High Integration," Nikkei Micro-Device, March issue, pp. 90-97

- Yoshioka, Hidemi (2004), "Contributing Factors for the Formation of International Competitiveness in the South Korean Semiconductor Industry: In Conformity with Changes in the Inter-Business Relationship between the Device and the Manufacturing Equipment Sectors," Asian Economy (Institute of Developing Economies, Japan External Trade Organization), Vol. 45, Issue 2, pp. 28-45, 2004